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COMPARATIVE AND NEUROPSYCHOLOGICAL RESEARCH IN HUMAN FACTORS PSYCHOLOGY

Gary Greenberg
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Human factors, a rapidly growing discipline since World War II, is usually defined as the study of human-machine interactions. One also sees the term "ergonomics" used in defining the field, and this stems from the discipline's roots in industrial engineering. Most would agree that the field today includes the study of human-computer interactions, artificial intelligence, cockpit design, workplace design, information-processing and cognitive processes, robotics, occupational stress, human error and reliability, etc. It seems clear that this is a discipline for the psychologist whose interests lie primarily with the human species.

But psychology has a long history of work with non-human animals, often with an eye towards human applications. The question arises whether there is a role for the comparative psychologist to play in the human factors field. This question is addressed in the papers in this special issue. These papers are based on a symposium, Comparative and Neuropsychological Research in Human Factors Psychology, held at the 1991 American Psychological Society meeting in Washington, D.C. Duncan White addresses the significance of his work on the visual system of cats for our understanding of human visual process and proposes an applied physiological psychology; David Washburn discusses his work with non-human primates, which are used to model human task performance, including that which is pertinent to space travel; Roger Thomas discusses issues of comparative intelligence, indicating the value of research with monkeys in understanding human intelligence and other cognitive processes; finally, Duane Rumbaugh and Shelly Williams provide a commentary about these papers by addressing the idea of continuity in psychology, i.e., to what extent can we generalize from one species to another, particularly in humans, in psychology.

I organized this symposium in an attempt to develop a broader defi-

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nition of human factors psychology than is currently in use, something that even the current president of the Human Factors Society recognized as necessary (Sheridan, 1991). Greg Moran (1987) recently proposed that we establish a discipline called Applied Comparative Psychology in which all human-animal interactions would be appropriate for investigation. Consistent with this is the idea that the study of human factors would include investigations of problems involving seeing-eye or hearing-ear dogs, zoo design for improving the educational mission of those facilities, the study of the behavior of sea animals that military and sports divers encounter, and so forth. This seems to be crucial as human factors programs move from their birthplace in engineering departments of new homes in psychology departments.

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THE CAT (*Felis catus*) AS AN EXAMPLE OF THE CONTRIBUTION THAT COMPARATIVE PSYCHOLOGY HAS MADE TO HUMAN FACTORS

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ABSTRACT: Human factors is an area of psychology, which systematically applies information about human behavior to designing environments for human use. The contribution that comparative psychology has made to human factors is demonstrated in this article using the example of the cat, which shows many of the neurophysiological and overt behaviors observed in humans. The article begins with a summary of exemplary basic research which illustrates similarities between the cat and humankind. The summary is followed by a discussion of various applications of these data to improve the human condition.

Human factors (ergonomics; engineering psychology) is the systematic application of information about human behavior. The objectives of this discipline are to improve the effectiveness and efficiency of human activities, and to improve certain desirable human conditions such as health, safety, and satisfaction (McCormick & Sanders, 1982). Human factors applies research data in such issues as development, mobility, vision, and socialization to realistic settings, modifying the environment to maximize the efficiency of human performance (Smith, 1990). Knowing how the human operates (i.e., the characteristics and needs of the "user") is fundamental to designing environments for human use, optimizing the relationship between technology and humankind, and facilitating the improvement of human life.

Comparative psychology is the study of similarities and differences in adaptive capacities between human and nonhuman animals, in an attempt to discover general laws of behavior in the context of evolution

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theory (Hodos & Campbell, 1969). Through this process, comparative psychology acquires insights into human behavior.

The cat (*Felis catus*) is a particularly appropriate species for this purpose. Cats are relatively tractable, amenable to human interaction (Imada, Tsukahara, & Imada, 1987; Mertens & Turner, 1988), inexpensive to maintain, and demonstrate many neurophysiological and overt behaviors observed in humans and other animals. As a result, the cat offers researchers an opportunity to control and manipulate the internal and/or external "human" environment, in ways that are ethically sound but not possible with humans of contingency-deficient computer simulations. Though nonhuman animal models of human behavior have their limitations (Lockery & Stich, 1989), data from neuroanatomical and neurophysiological investigations of the cat's central and peripheral nervous systems corroborate what is known about the human.

Research employing the cat to understand humankind is both diverse and voluminous. The specific areas of research overlap extensively, making an organized comprehensive overview elusive. On the other hand, the extent to which these areas interact indicates the richness of the contribution that cat-related research has made to our understanding of the human animal.

The purpose of this article is not to provide an exhaustive review of the cat literature, but instead to demonstrate the contribution that comparative psychology has made to human factors. Toward this end, exemplary basic research illustrating the many similarities between the cat and humankind will be discussed. Then attention will be given to the application of these data to improve the human condition.

SIMILARITIES BETWEEN CATS AND HUMANS

Learning, Memory, and Problem-Solving

Although the cat has not been used extensively as a research model to address learning, memory, and problem-solving processes, this general research area is mentioned first for two fundamental reasons. The first is the historical significance of Thorndike's puzzle box (1911) and K.U. Smith's 1930's visual discrimination studies. The second reason is that cat research, apart from neurological investigations, often uses a learning/performance task. In these cases the cat has been shown to perform in ways that are strikingly like human performance under similar conditions. For instance, both species are capable of visually discriminating between the members of at least seven test item pairs randomly presented in the same test session. In addition, cats and humans demonstrate a curvilinear rate of learning these discriminations as a function of test item complexity, with eight-sided figure pairs being the easiest (White & Ward, 1988). Bourassa and Weiden's (1985) investigations of orienting

responses and detection of thalamic stimulation also demonstrated that mechanisms of perceptual learning in the cat are consistent with those reported in humans. Bourassa and Weiden concluded by suggesting that input to cerebral cortex from sensory organs in either species is not a sufficient condition to produce conscious experience or discrimination.

Vision

The most extensive, and probably the most well-known, use of the cat as a model of human behavior is in the area of vision research. For example, behavioral experiments have revealed that cat and human spatial vision are comparable in several important ways. Both species possess stereoptic vision (Fox & Blake, 1971), both resolve about a five octave range of spatial frequencies (Blake, Cool, & Crawford, 1974), both show a trade off between spatial resolution and temporal resolution (Blake & Camisa, 1977), and both demonstrate a decline in acuity with retinal eccentricity (Blake & Bellhorn, 1978). Blake (1988) has noted that many of the hallmarks of mammalian vision were first discovered and explored in the cat. Some notable examples are retinal ganglion cells' center/surround organization (Kuffler, 1953), cortical neurons' orientation selectivity and massed binoculararity (Hubel & Wiesel, 1962), and the existence of parallel pathways originating with retinal X-, Y-, and W-cells (Shapley & Perry, 1986). Other similarities between the human and cat visual systems, resulting from analogous neuroanatomical and neurophysiological components, include contour and movement adaption, aftereffects, and recovery responses to prolonged stimulation with moving test items (Vautin & Berkley, 1977). These results continue to encourage the use of the cat to determine trigger features of human visual neurons.

Similarly, neural mechanisms for velocity discrimination in the cat have been suggested as a model for human motion perception (Orban, Kennedy, & Maes, 1981). Responses of feline X-cells of the LGNd to a small flashing test probe are likewise comparable to results from similar human psychophysical tests used clinically (Essock, Lehmkuhle, Frascella, & Enoch, 1985). These X-cell responses indicate that the size of a concentric background can have a pronounced influence on the sensitivity of both human and cat observers to a small probe.

Still other areas of cat vision research have addressed human depth perception (Mitchell & Baker, 1973) and flicker perception (Tyler, 1975), saccade awareness suppression (Riggs, Merton, & Morton, 1974) and main sequence saccades (Nelken, Heit, & Bridgeman, 1981), motion detection (Pasternak & Merigan, 1980), contrast sensitivity (Albrecht & Hamilton, 1982), the effects of positive and negative lens aberrations (Sivak & Kreuzer, 1983), vernier acuity (Swindale & Cynader, 1986), discrimination ability as a function of texture (Wilkinson, 1986), spatio-temporal aspects of the visual scene (Stanford, 1987), and subjective

contour discrimination (Orban, De Weerd, & Vandenbussche, 1990). In all these areas, the cat has displayed visual performance similar to that of humans.

Principles of visual development in cats also apply to humans. For example, Mitchell (1989) noted that an abrupt onset of stereopsis, and possibly vernier acuity, has been observed in both species; and visual acuity, as assessed with grating, develops gradually in primates and kittens. Similarly the development of cognitive performance, such as object permanence, has been observed in kittens and the flexibility of this animal's cognitive ability has been displayed, for example, by novel problem solving of visible displacement tests (Dumas & Dore, 1989). Though analogous behavior does not ensure analogous underlying mechanisms responsible for those behaviors (Innis & Staddon, 1989), similar behaviors do suggest similar adaptive capabilities and provide useful predictive models of behavior.

Audition

Though less attention has been given to the cat as a model for human audition, useful similarities exist. For example, comparable cat and human auditory vertex potentials have been found on a number of neuroanatomical and neurophysiological dimensions (Buchwald, Hinman, Norman, Huang, & Brown, 1981) and suggest that scalp-recorded frequency-following responses could be used to ascertain low-frequency hearing sensitivity in uncooperative humans (Gardi, Merzenich, & McKeon, 1979). Similarly, psychophysical methods investigating pitch perception of the cat have produced results which parallel human data (Chung & Colavita, 1976). Other auditory research employing the cat as a model for human behavior has been conducted in areas of binaural interaction (Hoppe & Langford, 1974), interaural intensive and temporal disparities (Wakeford & Robinson, 1974), sound localization (Kuwada, Yin, & Wickesberg, 1979), and auditory nerve-fiber responses to spoken-stop and nasal consonant-vowel syllables presented in four different levels of speech-shaped noise (Geisler & Gamble, 1989). This latter study found that consonants, being of smaller amplitude, are more affected by noise than are vowels.

Peripheral Nervous System

The peripheral nervous system of the cat has been found to be a valid model for neural mechanisms of human tactile and vibrotactile sensation (Hamalainen, 1983). The cat has also been used as a model to reconstruct the functional events occurring in nerves at the site of stimulation when human subjects reported pain relief (Swett & Law, 1983). In addition, the cat model has been used in kinesthetic research to acquire insights

into information regarding body part position, location, motion, speed, and direction (Burgess, Wei, Clark, & Simon, 1982). Such information is thought to contribute to body image (Gregory, Morgan, & Proske, 1988) and cognitive map construction (Mergner, Anastasopoulos, Becker, & Deecke, 1981).

Other Areas

Other areas of cat research, resulting in a better understanding of human (i.e., "user") characteristics, include: gustation (Boudreau, Oravec, & White, 1981), motor function (Frederickson, Smylie, Howell, & Lenig, 1978), split-brain behavior (Lepore, Ptito, Provencal, & Bedard, 1985), stroboscopic motion perception (de Bruyn & Orban, 1989), time perception (Macar, Vitton, & Requin, 1984), emotions (Bear, Rosenbaum, & Norman, 1986; Piazza, Crescimanno, Benigno, & Amato, 1986), sleep (Koridze & Nemsadze, 1982; Sinton & Petitjean, 1989), and evolution (Rush, 1988).

Comparative Research Summary

This overview of exemplary basic research illustrating similarities between cats and humans shows how the cat is a rich and varied source of knowledge about human neural functioning and behavior. As such, the cat is a valuable comparative model for suggesting useful modifications in environmental contingencies that result in improved human performance. To date, medicine has benefited most from the cat as a research model. These applications will be discussed along with other issues such as psychological, social and ecological welfare.

IMPROVING THE HUMAN CONDITION

Medical Models

The similarities between cat and human capabilities and behavior have been exploited to create better human conditions. For example, the cat is used extensively as a medical model to gain insight into the nature and treatment of human physiological and behavioral abnormalities. To illustrate, the cat is a valuable clinical model for understanding the neural mechanisms of cardiovascular disorders that may commonly accompany psychological stress (Tashiro, Tanaka, Fukumoto, Hirata, & Nakao, 1986). It has also been used to assess recovery following mild to moderate head trauma (Hayes, Clifton, & Kreutzer, 1989) and plasticity following gross and selective insult to the nervous system (Burgess, Villablanca, & Levine, 1986; Cornwell, Herbein, Corso, Eskew, & Warren, 1989). Other examples of the cat's substantial clinical impact are in developmental

monocular deprivation. The regimens of part-time reverse occlusion, which optimize recovery from the visual deficits induced by monocular deprivation in kittens, are similar to the patching of a good eye in order to induce the strengthening of a "lazy eye." This therapy is also like the patching regimens that promote the development of good vision in human infants following early corrective surgery for congenital unilateral cataracts (Mitchell, 1989). In addition, the cat has been used to develop a visual prosthesis for blind humans (Pollen, 1977) based on analogous cellular activity underlying visual perceptual events. Furthermore, similar visual pathways (i.e., "M" for fast-moving course visual forms and "P" for spatial detail of stationary or slow-moving visual forms) have clinical implications for diseases like glaucoma, Alzheimer's, and anisometropic amblyopia (Bassi & Lehmkuhle, 1990). Other clinical applications take advantage of the fact that P300, a measure of specific cortical activity, which is characteristic of both cats and humans, is a key to aging and disease processes. For instance, P300 changes functionally with age and is missing in Alzheimer's (Harrison & Buchwald, 1985).

Similar neurological investigations using cats have provided insights into other diseases such as "locked-in" syndrome (Zernicki, 1986) and hyperkinetic syndromes like Parkinson's Disease, Huntington's Chorea, and Gilles de la Tourette's Disease (McKenzie, Gordon, & Viik, 1972). Knowledge of (a) deficits in cognition and learning as a function of basal ganglia pathology (Olmstead, Villablanca, Marcus, & Avery, 1976), (b) chronic pain (Swett & Law, 1983), and (c) specific components of generalized corticorectal epilepsy (Gloor & Testa, 1974) have likewise come from cat research. In addition, this clinical model of human behavior has been used to investigate sleep deprivation and its effects in learning (Koridze & Nemsadze, 1982) as well as specific characteristics of sleep as manifested by sex and aging (Bowersox, Baker, & Dement, 1984) and depression (Beersma, Daan, & Van den Hoofdakker, 1984).

Cat models have indicated that degeneration of neural pathways is not required for the development of profound cognitive and motor impairments that characterize progressive dementia. Neurotransmitter-specific alterations are enough to cause diseases like Alzheimer's (Colye, Singer, McKinney, & Price, 1984). Similarly, when cats were administered psychoactive drugs (i.e., LDS, STP, DMT, psilocybin, and mescaline) in minimal doses, behavioral effects closely corresponded to those elicited by humans under similar conditions (Jacobs, Trulson, Stark, & Christoph, 1977). The cat has provided other examples of neurotransmitter-based aberrations as a model of amphetamine-induced psychosis and catatonic schizophrenia (Sudilovsky, 1975). Identification of auto-antibody against receptor sites for chemical transmitter substances in septal neurons of the cat also give support to the concept of schizophrenia as an immunological disorder (Garey, Heath, & Harper, 1974). In addition, feline somatosensory cortical responses to lithium carbonate levels, which

were within the range used clinically, mimic responses elicited in humans (Heninger & Sheard, 1976) and provide a model for further insight into the neurological bases of mania and depression.

Other Uses

Though knowledge of underlying neurological mechanisms is fundamental to understanding behavior, these mechanisms do not always predict the specific behaviors that they underlie (Innis & Staddon, 1989). A knowledge of environmental contingencies, identified as adaptive pressures on the animal, is also essential to predicting and facilitating behavior. With this awareness, and encouraged by the successful application of the cat as a medical model for treating human disorders, researchers have observed other cat behaviors that are potentially relevant to our species. For example, maternal protein restriction during late gestation and lactation in cats disrupts the development of orientation behavior in kittens by impairing locomotor function and increasing emotional responsiveness (Gallo, Werboff, & Knox, 1984). This condition further disrupts the development of mother-kitten social interactions and retards attachment formation (Gallo, Werboff, & Knox, 1980). Observations like these encourage health organizations to look for sources of potential protein restriction in human mothers (e.g., poor diet, natural catastrophes, political decisions) that could have grave consequences for the family unit and society.

Another interspecies behavioral analogy arises from the observation that cats are more active and self-groom more often when they receive attention (George, 1985). These behaviors are both indices of and contributors to the maintenance of good health. The knowledge regarding the effects of attention on personal health, coupled with studies suggesting that cats and humans have strong natural and learned affinities for one another (Imada, Tsukahara, & Imada, 1987; Mertens & Turner, 1988), has led to a treatment for humans who describe themselves as lonely and inadequate. These patients have reported an improved sense of self-worth, happiness, and productivity when given the responsibility of caring for a cat as a pet (Mahalski, Jones, & Maxwell, 1988). In this case, improvement of the human condition is achieved efficiently and economically by exploiting interspecies similarities and differences; cats are less intrusive on the person's private life and less demanding of time, space, effort, and money, than would be an employed human companion. Pets are also a popular subject of conversation, thereby facilitating social interaction.

Knowledge of the similarities and differences between species has led to the use of cats as sentinels of environmental conditions that threaten human health and encumber human performance (Schneider, 1972). Periodic monitoring of livestock, pets, and research animals has provided

early warnings of potential health hazards (Glickman, 1991). Cats, for example, age faster, have a higher metabolism, and are more susceptible to low doses of toxins than humans. Thus the interaction effects of aging and exposure to low toxicity in human living or work environments can be detected and treated in the early stages of development (Davidson, Parker, & Beliles, 1986).

Application Summary

As noted, there are many and diverse applications of our knowledge regarding the similarities and differences between cats and humans. Evidence in specific areas of human factors (e.g., medical, psychological, social, and ecological issues) illustrates the usefulness of our knowledge regarding the underlying contingencies of human behavior, derived from comparative studies using the cat.

CONCLUSION

At first glance, cross-species generalizations may seem suspect because species' classification is often a function of differences in biology and behavior. The apparent differences between cats and humans is striking. However, there are many practical uses of nonhuman animal models of human behavior, as well as many uses of the similarities and differences between species to improve the quality of life. For example, as noted in this article, numerous experiments using cats have suggested evidence of similar adaptive capabilities and similar mechanisms of perceptual learning. Also, many useful applications of knowledge, acquired from cats, in the areas of mental and physical health, have been demonstrated.

The cat is only one of a myriad of nonhuman animals studied by comparative psychologists. In this way, the cat has served yet another purpose: to provide a wealth of studies that suggest the magnitude of contributions comparative psychology has made, and will continue to make, to human factors.

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INTERACTIVE MODELS OF COGNITIVE ABILITIES OF MONKEYS AND HUMANS

(*Saimiri sciureus sciureus*;
S. boliviensis boliviensis;
Homo sapiens sapiens)

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ABSTRACT: First, squirrel monkey and human data were complementary in validating the hypothesized difficulty of oddity and sameness-difference concept hierarchies. Second, both were used to refute the hypothesis that numerousness discriminations (e.g., 7 versus 8 items) require counting and to support the hypothesis that such judgments involve a prototype matching process.

This article summarizes two areas of investigation of cognitive abilities where comparable tasks have been used with humans and squirrel monkeys. The first area of investigation involves hierarchies of oddity and sameness-difference tasks that were developed to increase the precision of measurement within level 6 of an eight-level hierarchy (Noble & Thomas, 1985; Steirn & Thomas, 1990; Thomas & Frost, 1983). The second area of investigation involves the study of conceptual numerosness judgments, where the theoretical question of interest is to elucidate the mechanism by which such judgments are made (Terrell & Thomas, 1990; Thomas, Fowlkes, & Vickery, 1980; Thomas & Lorden, 1993; Thomas, Phillips, & Young, 1990). The question is whether counting is necessary or likely to be involved, or whether a simpler mechanism can be used to explain the judgments.

A Learning/Intelligence Hierarchy

The cognitive tasks can be considered in the context of an eight-level hierarchy of learning processes that are believed to be synonymous with

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the fundamental intellectual processes (Thomas, 1980). Briefly, the learning/intelligence hierarchy was constructed from Gagné's (1972) hierarchy of learning processes and from Bourne's (1970) approach to the study of concept learning in humans. The eight levels are (1) habituation and sensitization, (2) signal learning also known as classical or Pavlovian conditioning, (3) simple operant learning, (4) chaining units of simple operant learning, (5) concurrent discrimination learning, (6) learning *class concepts* which are based only on the logical operations, affirmation and negation, (7) learning *relational concepts* that involve using class concepts in conjunctive, disjunctive, or conditional relationships or their respective complementary operations, and (8) learning relational concepts that involve using class concepts in biconditional relationships or its complementary operation, the exclusive disjunction.

Thomas's (1980) construction of the hierarchy included the following modifications of Gagné's (1972) and Bourne's (1970) approaches: (a) habituation and sensitization were added below signal learning, the bottom of Gangé's hierarchy, and (b) the concept learning hierarchy based on Bourne (1970; levels 6–8 above) was substituted for Gagné's highest three levels. Gagné's levels 6–8 were Concept Learning, Rule Learning, and Problem Solving, and they were defined by tasks that in most cases are likely to be unique to human abilities owing to their verbal or mathematical content. Thomas's substitution is justifiable because the concept learning hierarchy (levels 6–8 above) is fundamental to Gagné's levels 6–8; that is, the tasks that helped define Gagné's levels 6–8 can be reduced to the logical operations in levels 6–8 here.

Thomas (1980) also added an operational distinction between *absolute* and *relative* class concepts at level 6. Namely, the defining attributes of absolute class concepts are inherent in each discriminandum (e.g., each tree manifests its "treeness"). In contrast, the defining attributes of relative class concepts are not inherent in the discriminandum manifesting the correct choice but represent a relative property among the discriminanda (e.g., "oddity" as manifested in a triangle versus two circles or as manifested in a circle versus two triangles). Further details may be seen in Thomas (1980) and Steirn and Thomas (1990).

The hierarchy offers powerful advantages for comparative studies of intelligence. To summarize: (a) theoretically, the hierarchy can be used with any species from protozoans to humans, (b) it can be used relatively independently of the confounding effects of contextual variables such as sensory and motor differences, differences in motivation, etc., because it assesses processes and does not depend on specific tasks; that is, each assessment task can be adapted to each species' unique sensory, motor, motivational, etc., requirements, (c) it encompasses all of the fundamental learning processes, (d) it can be applied retroactively or proactively to any learning study whether or not the study was planned in the

context of the hierarchy, and (e) it can be used for ontogenetic or phylogenetic comparisons.

It is likely that all vertebrates are capable of at least some degree of success in concurrent discrimination learning, level 5 (see Table 4, Thomas, 1986). It is also likely that cognitive and intellectual differences among mammals will be found among the *conceptual* abilities represented at levels 6–8. Owing to the latter, the research in my laboratory has been focused on the abilities of nonhuman animals to learn to use class and relational concepts.

Oddity and Sameness-Difference Concepts

There are systematic ways to increase the cognitive demands and, therefore, the precision of measurement within levels 7 and 8, and sublevels of 7 and 8 can be developed without theoretical limit (see Tables III and IV, Thomas, 1980). However, ways of distinguishing abilities within or between species within level 6 are not immediately obvious. Since it seems likely that many species will reach a ceiling within level 6 (i.e., be able to use class but not relational concepts) it seems essential to find systematic ways to increase the precision of measurement within level 6. We have investigated two related types of tasks, oddity and sameness-difference (hereafter, SD).

With one exception that is relatively minor and will be discussed below, systematic hierarchies of oddity and SD tasks can be constructed by manipulating discriminative cues based on attributes such as color, form, and size. The cues can be manipulated to be (a) *relevant* to, (b) *constant* and, therefore, uninformative, or (c) *ambiguous* to the discrimination being required. By ambiguous, it is meant that the cues vary in an uninformative way. While being uninformative, constant cues are not distracting, but ambiguous cues are likely to distract.

The aforementioned exception to the systematic construction of oddity or SD hierarchies occurs when one makes the transition from *identical* nonodd or sameness discriminanda to nonodd or sameness discriminanda that are *not identical* but have more attributes or properties in common than they have with the odd or difference discriminanda. In this instance, but only at the transition point, the increasing difficulty is not determined logically but must be determined empirically. This will be discussed further below.

For simplicity, the following discussion is only in terms of oddity problems. However, everything that is written here about oddity problems, except as noted, can be applied equally to SD problems provided "odd" and "difference" are used interchangeably and provided "nonodd" and "sameness" are used interchangeably.

In a typical three-discriminanda oddity task, each trial consists of presenting the odd discriminandum and the two nonodd discriminanda.

For example, one might use two red cubes and one blue ball where the cubes are the same size but are smaller than the ball. In this example, the color, form, and size cues are all relevant; that is, each can be used to distinguish the odd from the nonodd discriminanda. Alternatively, one might hold one or two of the cues constant, thereby leaving two or one relevant cues, respectively. While, empirically, the difference between the odd and nonodd discriminanda based on one cue alone might be as obvious and easy to discriminate as when all three cues are relevant (as seems to be the case for squirrel monkeys and humans), theoretically, a problem with three relevant cues should be easier than a problem with two or one relevant cues. Of course, it is possible and seems likely that some species or younger subjects within a species will find that a one-relevant-cue problem is more difficult than a two- or three-relevant-cue problem.

When the transition is made such that the discriminanda no longer include identical nonodd objects, the discriminations that are required become more difficult. For example, two cubes might be the same smaller size compared to one larger ball (thus, size and form remain relevant) but the objects might each be of a different color. In our research, we have varied randomly from trial to trial which types of cues will be relevant, constant, or ambiguous. To conclude with these examples, we might have a small red cube, a medium-sized blue pyramid, and a large red ball on one trial (thus, color determines the odd object) and then have a small green pyramid, a middle-size red ball, and a large blue ball on the next trial (thus, form determines the odd object). It is obvious that such discriminations are of a different order of difficulty compared to those where the nonodd objects are identical.

Theoretically, there should be increasing cognitive demands and, therefore, increasing performance difficulty as one goes from three cues to two to one relevant cue or as one goes from one to two ambiguous cues, etc., even if empirically such changes do not always challenge all species. As suggested earlier, the logical structure of the hierarchy falters when one changes from identical to nonidentical nonodd or sameness discriminanda. The logical progression from levels 1 to 3 (based on decreasing relevant cues) and from levels 4 to 6 (based on decreasing relevant cues and increasing ambiguous cues) seems clear. However, logically it is not possible to say whether problems with one relevant and two constant cues would be easier or harder than problems with two relevant and one ambiguous cues. Thomas and Frost (1983) hypothesized that the ambiguous cue would cause more difficulty and designated the two-relevant, one-ambiguous cues problems as being at level 4 leaving the one-relevant and two-constant cues problems to be at level 3. Therefore, among our goals was to determine empirically whether the oddity hierarchy as constructed would lead to systematic performance differences.

Before discussing our empirical research, it is useful to add the following two general points. First, up to now the oddity (and SD) hierarchies have been discussed in terms of varying color, form, and size. By varying these three properties, one can construct a 6-level hierarchy (see illustrations in Steirn & Thomas, 1990). By adding another property such as number, one can construct a 10-level hierarchy (an example of a trial might be: two small red balls are one discriminandum, two small red balls are another, and three large blue cubes is the third discriminandum on one particular oddity trial). Other properties could be added (e.g., placing the pairs of small red balls on a white square and placing the three large blue cubes on a white circle) making a 15-level hierarchy. Additional properties could also be introduced and hierarchies with more levels could be constructed.

Second, while the oddity of SD hierarchies can be constructed in a highly similar manner, there is a significant conceptual difference between them. Namely, as long as a pair of discriminanda manifesting sameness consist of identical objects, the discrimination between the sameness and difference pairs of objects can be made as an absolute class concept; that is, it is not necessary for an animal to compare the sameness and difference discriminanda in order to affirm which pair of objects manifest sameness and which manifest difference. It is only when the SD tasks involve nonidentical sameness pairs that comparison between discriminanda becomes necessary. Oddity, however, always requires comparison and is, therefore, always a relative class concept.

The difference between absolute and relative class concepts is important, because nonprimate animals have succeeded on tasks requiring the use of absolute class concepts, but owing to methodological confounds it is unclear whether any nonprimate animal has ever succeeded on a task that requires the use of a relative class concept (see Steirn & Thomas, 1990, for further related discussion). If the capability of learning absolute and relative class concepts represents a "breakpoint" in phylogenetic cognitive development, then having a series of tasks (viz., the SD hierarchy) which makes the transition from absolute to relative class concepts in a systematic way is exceptionally valuable.

Empirical Tests of the Oddity and SD Hierarchies using Squirrel Monkeys and Humans. Thomas and Frost (1983) trained squirrel monkeys on oddity tasks beginning with the level 1 task and proceeding in succession to the level 6 task. Training on the level 1 task was not limited in the number of trials, but all monkeys met the joint-criterion (see below) in 1,200 trials or less. Since succeeding tasks should involve considerable transfer of training from level 1, a limit of 400 trials (ten sessions of 40 trials each) was planned if they failed to meet the joint criterion of 36 correct in a 40-trials session and a significant run of errorless trials ($p < .01$).

Details of the monkeys' performances may be seen in Thomas and

Frost (1983; especially Table 2). In summary, we found that, as predicted, each succeeding level was more difficult than the previous one, except that, contrary to prediction, level 4 (the first with ambiguous cues) was easier than level 3 and was as easy as levels 1 and 2.

However, we had overlooked a reasonable noncognitive explanation. Male squirrel monkeys are deficient in color vision (Jacobs & Neitz, 1985), and level 3, as noted above, had one relevant cue while level 4, even with its ambiguous cue, had two relevant cues. Given that by chance the relevant cue at level 3 would be a color cue on one-third of the trials, the monkeys' color vision deficiencies likely accounted for their poorer performances on level 3. This also explains in part their poorer performances on levels 5 and 6 which, like level 3, had only one relevant cue. However, color vision deficiencies do not provide the complete explanation, because their performances on level 6 were worse than those on level 5.

In view of the confounding role of color vision deficiencies in the squirrel monkey, Noble and Thomas (1985) decided to test the empirical validity of the oddity hierarchy using humans. After screening the human participants for color vision deficiencies, Noble and Thomas (1985) tested each person on only one of the oddity tasks; 10 people were tested on each task. Generally, the tasks at all six levels were too easy for our adult humans to provide clear differences in performance at each level. Nevertheless, the data provided support for the hierarchy. For example, level 6 required more mean trials to criterion than level 5, although the difference was not significant, but both levels 5 and 6 differed significantly from each of levels 1-4, etc.

Most importantly, in view of the unexpected but explainable (in terms of color vision) finding that the monkeys found level 4 easier than level 3, there was evidence that the humans found level 4 more difficult than level 3. Specifically, their response latencies were significantly longer at level 4 than at level 3, and they approached statistical significance ($p < .08$) in taking more trials to criterion on level 4 than on level 3.

Our most recent attempt to validate both the oddity and SD hierarchies using humans involved manipulations that were intended to increase task difficulty in a way that might provide clearer validation of the predicted differences between successive levels (Steirn & Thomas, 1990). Specifically, each person was trained on a random sequence of trials that were administered concurrently from *three* levels (either 1-3 or 4-6). This was done for some using oddity problems and for others using SD problems.

Despite the added complexity of mixing trials from three task levels, Steirn and Thomas (1990) reported the same general findings on the oddity tasks that were reported by Noble and Thomas (1985). For example, differences in percentages correct and in response latencies as a function of task level were usually in the predicted direction, but the

differences were not usually significantly different between successive levels. Comparable to Noble and Thomas's findings on the oddity tasks, response latencies were significantly longer on level 4 trials than on level 3 trials. Although the difference in percentages correct between levels 3 and 4 were in the predicted direction, they were not statistically significant.

Important findings emerged on Stein and Thomas's (1990) SD tasks. The differences between levels 3 and 4 on both the percentage correct measure and the response latency measure were statistically significant in the predicted direction. This is important because, as discussed earlier, levels 1-3 in SD tasks can be done on an absolute class conceptual basis but levels 4-6 require that they be done on a relative class conceptual basis.

Obviously, in view of the tasks being generally too easy for adult humans and in view of the male squirrel monkey's visual problems, further research on the oddity and SD hierarchies is needed. Future research might be done with young humans or with primates that have trichromatic color vision that could validate and expand the usefulness of the oddity and SD hierarchies.

Conceptual Numerousness Judgments

The typical numerosness judgment task used with animals has been to display arrays of entities (e.g., black dots on a white background) and have the animal discriminate between an array with one number of entities and an array with another number of entities. There has long been an interest in animals' abilities to make such judgments (Honigman, 1942; Salman, 1943; Wesley, 1961), but Wesley concluded that only Hick's study (1956) had been sufficiently free of confounding variables to conclude that the animals' judgments were based on numerosness. Hicks reinforced rhesus monkeys (*Macaca mulatta*) for choosing arrays of 3 items versus arrays of 1, 2, 4, or 5 items. While there have been some well controlled studies (Davis & Pérusse, 1988; Thomas & Lorden, 1993) poorly controlled studies have been prevalent.

Typical confounding variables in the early studies were (a) having dots of uniform size where cumulative area or differential brightness were possible discriminative cues and (b) failing to control for the odor of the reinforcers which may have cued the animal to the correct choice. Thomas and Lorden (see Table 1; 1993) listed these and other possible confounding cues or interpretations that must be avoided before attributing numerosness judgments to animals.

Thomas, Fowlkes, and Vickery (1980) incorporated the appropriate controls and used systematic training procedures to determine the squirrel monkey's likely upper limit in ability to discriminate consecutive numerosness arrays. Both monkeys discriminated seven versus eight

dots at a high level of success (90% based on 45 correct in a 50-trials session; hereafter, the form 7:8 will be used to describe such discriminations). One of the monkeys met the 90% criterion on 8:9 but failed to meet criterion on 9:10 within the preset limit of 500 trials, although he performed at a level of about 75% correct on the 9:10 task.

Subsequently, Terrell and Thomas (1990) used the number of sides of randomly constructed polygons as discriminanda. Their monkeys' best performances were that two of four monkeys met a 90% correct criterion on 7:8 (36 correct in a 40-trials session), one met the criterion on 6:7, and one met the criterion on 5:7.

Processes to Explain Numerousness Judgments. Gallistel (1988, 1990) has argued forcefully that numerosness judgments of dot arrays are based on counting. He has strongly opposed processes such as the prototype matching one that we propose to explain such judgments. Central of Gallistel's argument is the reported serial increase in response times as the number of entities in an array increases. According to Gallistel (1988), citing data from Mandler and Sheeo (1982):

It takes 30 msec longer to recognize twoness than to recognize oneness, 80 msec longer to recognize threeness than twoness, 200 msec longer to recognize fourness than threeness and from fourness on up there is an increment of 350 msec per item (p. 586).

However, not all studies have shown serial increases in response times, and the procedures used by Mandler and Sheeo (1982) may not be applicable to explain the results of Thomas et al. (1980) and Terrell and Thomas (1990).

An alternative explanation to counting that Terrell and Thomas (1990) proposed was that their monkeys acquired prototypes for absolute class concepts such as "threeness," "sevenness," etc. and then applied them to make accurate numerosness judgments of new arrays of entities. That 7:8 emerged as a common upper limit in both the dot and sides-of-polygons studies suggested the possibility of an underlying common process.

The upper limit of numerosness prototype acquisition and use is probably related to information processing channel capacity as exemplified in Miller's (1956) well known "magical number seven, plus or minus two." Individuals can then learn to use the acquired prototypes to affirm the numerosness of *new* arrays of entities by matching each new array with its numerical prototype. Monkeys will likely require more trials to acquire and use prototypes than humans, because monkeys lack the prior experience with number that is typical of humans. Based on our findings with monkeys and humans there is no reason to think that the monkeys' channel capacity for numerosness will differ significantly from that of humans. After discussing why we proposed a noncounting

process explanation, I will report our findings from an experiment that we conducted to test the response latency hypothesis.

Terrell and Thomas (1990) proposed a noncounting explanation of our monkey data, because our monkeys did not have the requisite experience and skills to count. We based the requisite skills on three of the five principles of counting presented by Gelman and Gallistel (1978), namely, the one-to-one correspondence, stable-order, and cardinal principles. Gallistel later (1990) indicated that the fourth and fifth principles, order-irrelevance and abstraction, are not essential to demonstrate counting, a position I have supported (Thomas, 1992).

One-to-one correspondence requires that the individual apply unique tags (such as but not limited to Arabic numerals) to the entities being counted. Gelman and Gallistel (1978) apparently did not require direct evidence that the individual had acquired or used the tags nor, therefore, that they had applied them in stable order. However, direct evidence is necessary, because there is an alternative noncounting process, prototype matching, that can explain the animals' numerosness judgments. Our monkeys had no opportunity to learn or apply tags, and most importantly, they did not need to learn and use tags, because the prototype matching process is simpler than counting. Prototype matching is also consistent with the way other kinds of class concepts are likely to be acquired and used by animals.

Empirical Tests of Counting Versus Prototype Matching Explanations. We (Terrell & Thomas, 1990; Thomas & Lorden, 1993; Thomas, Phillips, & Young, 1990) hypothesized that if an individual can make a discrimination between two arrays accurately (as defined by being correct on 90% of a set of trials), the judgments for the two arrays will be made with similar response latencies. Additionally, according to Gallistel and based on the data in the quotation above, it would require $(x + 1,360)$ msec to judge sevenness and $(x + 1,710)$ msec to judge eightness. The value, x , represents the time for the oneness judgment that was not specified in the quotation from Gallistel.

Since the data needed to examine the relationship of response times to numerosness judgments could be obtained more easily with humans than with squirrel monkeys and since humans were the subjects in the studies on which Gallistel (1988, 1990) based his arguments, we (Thomas et al., 1990) elected to test the response latency hypothesis by using humans. We used both dots and sides of polygons as the numerosness discriminanda. Since the findings were generally consistent for both dots and sides of polygons and in the interests of brevity and clarity, most of the discussion here will be limited to the dots.

Each subject was tested first on the 3:4 number-pair and then on another number-pair discrimination, either 4:5, 5:6, 6:7, 7:8, 8:9, 9:10, or 10:11. If dots were tested first, then the person was subsequently tested

on polygons and vice versa. Twenty people were tested on each number-pair (except, of course, all 140 subjects were tested on 3:4).

A numerosness array was presented tachistoscopically for 200 msec and was followed immediately by a masking stimulus the use of which was intended to prevent counting based on afterimages. The dots were varied in size so cumulative area and differential brightness could not be used reliably as discriminative cues, and all trials consisted of unique arrays so pattern learning was precluded.

The person was told before each set of trials which of two numbers would be presented. Single exemplars of a number-pair were presented one at a time in a randomized order, and the individual was instructed to press a button that corresponded to its number as quickly as possible. Participants were trained to a criterion of 90% correct in a block of 20 consecutive trials or until a maximum of 200 trials per number-pair had been administered. The following results are based only on those who reached the 90% criterion.

Our specific prediction was that the response times for *consecutive* arrays would not differ, but there were no significant differences in mean response times for *any* array of numbers from 3 to 11. Mean response times ranged from 720 msec for arrays of 10 (in the 9:10 problem; based on the 3 of 20 people who reached criterion) to 1,010 msec for arrays of 11 (in the 10:11 problem; based on 2 of 20 participants). As might be expected there was a general decrease in the number of people who reached criterion as the size of the number-pair increased. For example, all 140 met the criterion on 3:4 and 20 met the criterion on 4:5, but only the few noted above met the criterion on the 9:10 and 10:11 problems. Also, as might be expected, there was a general increase in the mean number of trials to criterion as the size of the number-pairs increased from 30 trials on 3:4 to 170 trials on 10:11.

According to Gallistel (1988, 1990), we should have found response times that increased serially as the number of entities in an array increased, but we did not find significant differences in response times across our arrays. Gallistel also predicted response times that were considerably longer than we obtained. According to Gallistel, we should have found response times of approximately $(x + 2,760)$ msec for arrays of 11 dots but our mean response time for 11 dots was only 1,010 msec. Since the serial increase in response times was central to his justification for the counting explanation, our data refute Gallistel's basis for the counting explanation.

As a closing point in support of the prototype matching process, I urge the reader to experiment informally with prototype acquisition and use. For example, one can easily view at a glance (or view with the deliberate intention to avoid counting) arrays of items, such as clusters of farm animals in a field as one passes in an automobile or train, and try to guess accurately the number of items. Of course, one can then count the

items to confirm the number. I believe that you will discover that your judgments for small arrays (e.g., 3, 4, and 5 which are probably learned passively during one's lifetime) are usually accurate and that with practice you will increase the number of items in arrays that can be judged accurately. Based on our findings, most of us will peak in accuracy at about 6:7 for consecutive numerosness judgments, but there are occasional savants who acquire and use prototypes for numbers as high as 10 and 11 or possibly higher. Practice may improve skill up to a limit, but I suspect that limit is within a small extension of Miller's (1956) magical number 7 plus or minus 2. Neither our research so far nor this informal experiment address discriminative numerosness judgments that are nonconsecutive (e.g., 25 vs. 50 items) and that can likely be learned accurately as well.

Conclusion

The present research has suggested the feasibility of developing and testing models of cognition and intelligence that can be applied to human and nonhuman animals. While the usual direction of animal-human model research has been to seek an animal model to test some question of consequence to humans, we have used humans as models to investigate issues that arose in animal research. Of course, the fundamental processes addressed in our research apply equally to humans and nonhuman animals.

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HUMAN FACTORS WITH NONHUMANS: FACTORS THAT AFFECT COMPUTER-TASK PERFORMANCE

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ABSTRACT: There are two general strategies that may be employed for "doing human factors research with nonhuman animals." First, one may use the methods of traditional human factors investigations to examine the nonhuman animal-to-machine interface. Alternatively, one might use performance by nonhuman animals as a surrogate for or model of performance by a human operator. Each of these approaches is illustrated with data in the present review. Chronic ambient noise was found to have a significant but inconsequential effect on computer-task performance by rhesus monkeys (*Macaca mulatta*). Additional data supported the generality of findings such as these to humans, showing that rhesus monkeys are appropriate models for human psychomotor performance. It is argued that ultimately the interface between comparative psychology and technology will depend on the coordinated use of both strategies of investigation.

There are two general interpretations for the notion, suggested by the title of this article, of doing human factors research with nonhuman animals. In the first, the nonhuman animal-to-machine interface is studied in a style mirroring that of traditional human factors research. That is, "human factors-type" research can be conducted with nonhuman animals to the end of identifying factors that influence the animal-to-technology interaction. According to the second interpretation of "human factors with nonhumans," nonhuman animals are used as surrogates for or models of human performance. It will be argued in the present article that both meanings of the phrase are critical for the study of behavior and performance.

Factors that affect the nonhuman animal-to-technology interaction should—and increasingly can—be identified and examined using many techniques comparable to those employed in research with human op-

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erators. At our laboratory for example, we have conducted a series of experiments to discover the factors that affect a rhesus monkey's interaction with the Language Research Center's Computerized Test System (LRC-CTS; Rumbaugh, Richardson, Washburn, Savage-Rumbaugh, & Hopkins, 1989; Washburn & Rumbaugh, 1992a). The LRC-CTS is a computer-based test system in which individuals (human or nonhuman primates) respond to computer-generated stimuli by manipulating a joystick. Variables such as computer speed, monitor type and size, joystick size and angle of orientation, incentive, and social arrangement—all rather standard types of variables in human factors research—have been systematically manipulated to determine the effects on monkeys' computer-task performance. In addition to permitting the design and construction of better test stations, this information has frequently resulted in valuable basic psychological science.

MONKEY-TO-MACHINE INTERFACE

To illustrate this type of investigation, we conducted an experiment to determine the effects of ambient noise on computer-task performance. For a variety of reasons, chronic conditions of high ambient noise, a feature of many environments, might be expected to influence performance. Under such conditions, task auditory feedback may be made inaudible, subjects may be unable to obtain adequate rest or sleep, might become distracted by features within the noise, or chronic noise may affect a person's psychological well-being; any of these effects might be expected to compromise task performance. On the other hand, there is a literature (Broadbent, 1978; Poulton, 1978) suggesting that at least transient levels of background noise can increase an individual's general arousal and improve performance.

Experiment 1

Animals. To examine these predictions, two 9-year-old male rhesus monkeys (*Macaca mulatta*, Abel and Baker) were tested. Abel and Baker have received extensive training and testing using the LRC-CTS (e.g., Washburn & Rumbaugh, 1991, 1992b), and their performance levels on each of the tasks in this experiment (see below) were asymptotic. Each monkey worked on the tasks ad libitum in his home cage for 24-hr/day, during which time the tasks and water were continuously available. Supplemental chow and fruit were provided daily so that neither animal was deprived below their normal weights for purposes of testing.

Apparatus and Tasks. Testing was conducted using the LRC-CTS, a battery of software tasks and the computer hardware required to administer them. Two test stations were used (one for each animal), each configured as described by Washburn and Rumbaugh (1991) except that



FIGURE 1. Test configuration used with the rhesus monkeys in these experiments. The monkey reaches through the cage mesh and manipulates a joystick to respond to computer-generated stimuli on the screen. A LASER trial can be seen on the screen.

AST 386-SX computers were used. These computers controlled the delivery of 97-mg fruit-flavored pellets (P. J. Noyes Co., Lancaster, NH) through a Gerbrands 5110 dispenser (Gerbrands Corp., Arlington, MA), and of sound feedback through a speaker/amplifier (Radio Shack 32-2031a). Stimuli were presented on a color monitor, to which the monkeys responded by manipulating a standard analog joystick in accordance with task demands. Figure 1 depicts this testing configuration.

Performance was assessed using a battery of computerized tasks. The tasks were available via a menu format called SELECT (Washburn, Hopkins, & Rumbaugh, 1991). In the SELECT task, an array of icons is presented on the screen; selection of any icon, made by manipulating the joystick so as to bring a computer-generated cursor ("+"") into contact with the icon, resulted in 5 trials of a corresponding task, followed by re-presentation of the SELECT menu. Task icons were provided for each of the tasks in Table 1. Detailed discussion of each of these tasks except HOLE can be found elsewhere (Washburn & Rumbaugh, 1991).

Procedure. The animals were tested on this battery of tasks under each of two conditions (baseline versus noise). Testing under normal levels of background noise was conducted for the baseline condition. Sound pressure level was measured with a Brüel and Kjær Modular Precision Sound Level Meter to be approximately 50 db in the baseline condition, with occasional brief peaks of sound pressure not in excess of

TABLE 1
Tasks Used in the Present Experiments

<i>Procedure</i>	<i>Task name</i>	<i>Description</i>
Tracking	SIDE	Move the cursor into contact with a stationary target.
	CHASE	Move the cursor into contact with a moving target.
	PURSUIT	Catch and maintain unbroken contact with a moving target for 0-12 sec (randomly selected each trial).
	LASER	"Shoot at" a moving target; moving the joystick causes a "shot" to be fired.
	HOLE	Move the cursor into contact with a moving target; the target can move through a barrier (a large circle positioned in the center of the screen) but the cursor cannot, requiring the operator to circumnavigate the barrier to catch the target.
Matching-to-sample	MTS	Bring the cursor into contact with a stimulus (the sample), then select a matching stimulus from two choices.
Delayed matching-to-sample	DMTS	Same as MTS, but with a randomly selected delay (0-40 sec) before selecting the matching stimulus.
Delayed responding	DR	Two stimuli presented on the screen; bring the cursor into contact with the flashing stimulus (the sample); following a randomly selected delay (0-40 sec), select the matching stimulus.
	SELECT	A menu of icons, with each icon corresponding to one of the above tasks; selection of one icon results in 5 trials of the corresponding tasks and subsequent presentation of the SELECT menu.

70 db (e.g., for the sound feedback accompanying pellet delivery for a successfully completed trial).

For the chronic ambient noise condition, a Commodore 128 computer was used to generate constant "white noise." This noise was amplified through a speaker/amplifier (Radio Shack 32-2031a) to produce an average sound pressure level of 89 db (range 88–90 db) from anywhere around the two test stations. This noise level was maintained 24-hr/day during each day of chronic ambient noise testing.

These two conditions were manipulated in an ABBA experimental design (baseline-noise-noise-baseline) for both animals. Each condition lasted 4 days. The order of task administration within days was determined by each animal according to individual preferences.

Results. No effect was seen of noise condition on the number of trials performed each day. On average, 1206 trials/day/animal were obtained in baseline testing (standard deviation = 220), whereas each animal produced 1247 trials each day with 89 db ambient noise (standard deviation = 148). No evidence was found for Condition \times Day interactions that might have suggested progressive change due to sleep loss, adaptation, or distress. Additionally, although comprehensive observations were not made, no obvious shift in work schedule or sleep pattern was apparent, as the monkeys seemed to adapt to the changes in ambient noise without affect.

A consistent but slight increase in the amount of time required to capture targets in the SIDE, CHASE, LASER, and HOLE tasks was observed for the 89-db noise condition (Table 2); however, this difference did not approach statistical significance. Overall, the response times in both conditions were within the normal ranges for the two test subjects on these tasks.

Analysis of the accuracy of responding also revealed a slight compromise in responding under conditions of 89-db ambient noise to the PUR-SUIT, MTS, DMTS, and DR tasks (Table 2). Given at least 3000 observations per task, these differences could be considered to be statistically significant (using z -scores, $p < .05$), despite the fact that they average less than one-half standard deviation (i.e., less than 5% of the baseline performance). Using a conservative statistical analysis (analysis of variance using task and condition as within-subject factors), the differences between conditions are marginally significant, $F(1, 14) = 4.40$, $p = .06$. In any case, it is clear that performance was excellent across animals, tasks, and experimental conditions.

Discussion. It is concluded that chronic exposure to ambient levels of noise at an average sound pressure level of 89 db has a detectable but inconsequential effect on rhesus monkeys' computer-task performance. It is noteworthy, given the small N and only 8 days of testing per condition, that the computer-task measures were sufficiently sensitive to detect the small but reliable differences revealed in this study. It is

TABLE 2
Results from Experiment 1

<i>Task/measure</i>	<i>Baseline</i>	<i>89 db noise</i>
Number of trials/day	1206	1247
SIDE mean response time	0.74 sec	0.75 sec
CHASE mean response time	2.18 sec	2.53 sec
LASER mean response time	4.81 sec	4.45 sec
HOLE mean response time	0.97 sec	0.98 sec
PURSUIT mean percentage of errorless trials	89%	85%
MTS mean percentage correct	97%	94%
DMTS mean percentage correct	94%	91%
DR mean percentage correct	89%	85%

equally important to note, however, that performance levels in all conditions were high and within the normative range for the two monkeys. Thus, the differences reported here, while genuine, are of little practical consequence.

ANIMAL MODELS OF HUMAN FACTORS

It should be clear from this extended example that factors that influence—or fail to influence—the interface between nonhuman animals and machines is as open to examination as are the traditional areas of human factors research. Perhaps less obvious or cogent is the potential applicability of findings of animal-to-machine factors to human operators. For example, given the results of Experiment 1 suggesting that chronic ambient noise produces slight but detectable disruptions of computer-task performance by rhesus monkeys (at least with respect to accuracy), how confidently might we expect similar findings with human subjects?

There are numerous reasons why it would be advantageous to be able to test nonhuman animals and generalize to human operators. The practical, experimental, and perhaps ethical costs of testing humans under conditions of chronic ambient noise, for example, outweigh the costs of doing the same type of research with rhesus monkeys. On the other hand, the generality of data between species is, of course, limited by numerous factors. Even in the absence of qualitative differences between humans and other primates for instance, such as in the capacity for speech and the natural development of language, extensive quantitative differences remain that must be mapped or scaled. Moreover, in the presence of comparable performance between species, further investigation is re-

quired to determine whether the overt behavior is an accurate reflection of comparable processes—of some common continuum on which all organisms and competencies might fall.

The generality of the findings of Experiment 1 to humans might be challenged by several researchers who have posited qualitative differences between humans and monkeys in psychomotor performance. Tasks such as CHASE, PURSUIT, LASER, and HOLE were designed to permit investigation of psychomotor processing (eye-hand coordination, tracking, target prediction); however, at least three teams of investigators have reported that rhesus monkeys provide an inappropriate model for human psychomotor functioning. In the most recent of these experiments, Jaeger (1980) trained rhesus monkeys to respond to unpredictably moving targets in a compensatory tracking task. Human performance on the same task was also assessed. When target movement was made predictable for both groups, performance by humans showed a much larger benefit than did performance by rhesus monkeys. Given this striking difference in the degree to which the two species benefitted from predictably moving targets, Jaeger concluded that humans alone can be characterized as "predictor-operators," echoing the findings (and in many respects the procedures) of the earlier investigations (Brooks, Reed, & Eastman, 1978; Fuchs, 1967).

At least two objections to this conclusion can be offered, however. The first is that, having been trained with unpredictable target movement, it seems unsurprising that the monkeys showed little performance benefit from predictable movement. The monkeys were essentially trained to respond nonpredictively, whereas humans use experience from other sources to recognize regularity in target movement. Consequently, it seems reasonable to suggest that animals trained to respond to predictably moving stimuli might show performance disruption under conditions of unpredictable target movement. This possibility, which was in fact suggested by Jaeger (1980), was directly examined in Experiment 2.

Second, it appears that performance by monkeys *does* show slight benefit from predictable versus unpredictable target movement in these studies, albeit in each case the improvement is not as marked as with humans. For example, the rhesus monkeys studied by Jaeger (1980) both performed best in the predictable movement condition, although standard statistical measures were not reported to reveal whether this difference approached statistical significance. Only in comparison to human performance as a standard was it determined that rhesus monkeys did not predict. Thus, it remains possible that both humans and rhesus monkeys can be described as predictor-operators, notwithstanding residual quantitative differences in the degree to which or the accuracy with which they respond predictively. This hypothesis was tested in Experiment 3.

TABLE 3
Mean Response Times and Error Measures from Experiment 3

<i>Task</i>	<i>Data</i>	<i>Rhesus</i>		<i>Humans</i>	
		<i>Predict</i>	<i>Random</i>	<i>Predict</i>	<i>Random</i>
CHASE	Response time	2.31 sec	3.06 sec	2.10 sec	2.92 sec
LASER	Response time	3.98 sec	10.37 sec	4.06 sec	12.12 sec
LASER	Number of shots	2.50	13.96	2.71	11.56
PURSUIT	Percent of errors	30%	45%	6%	25%

Experiment 2

Monkeys. The two rhesus monkeys of the previous experiment were again tested. Unless otherwise noted, conditions of testing for this experiment were identical to those described for Experiment 1.

Additionally, human volunteers from the undergraduate pool at Georgia State University (ages 18 to 35 years, 7 women and 3 men) were tested. Identical tasks and comparable apparatus and procedures were used with these people as were used with the monkeys.

Apparatus and Tasks. As in the previous experiment, all were tested using the LRC-CTS and the CHASE, PURSUIT, and LASER tasks. These tasks were designed to measure the speed and accuracy with which individuals intersect and track moving targets. Response latency (the time from trial onset to the first movement of the joystick) and response time (RT; the time from the first joystick movement until the end of a trial) was measured by all tasks on each trial. Additionally, the number of PURSUIT errors (occasions in which the cursor was allowed to drift away from the moving target) and the number of LASER shots required to hit the target were maintained by these tasks.

Procedure. From each monkey, 10 blocks of 100 trials were collected for each task under each condition (predictable and random target movement; 6000 trials per subject). Each human similarly performed 1 block of 100 trials per condition and task, for a total of 600 trials per person. It is interesting to note that the number of trials per condition is limited entirely by how many trials humans will voluntarily produce; the monkeys each perform over 1200 trials per day across tasks. For all, the order of administration, both for tasks and for experimental conditions, was randomized.

Results. An ANOVA was performed for each task using condition (predictable versus random target movement) as a within-subject variable and species (humans versus monkeys) as a between-groups variable. The results are summarized in the top panel of Table 3. Performance on the CHASE task was significantly better when the target moved pre-

dictably than when it moved randomly, $F(1, 18) = 9.88, p < .01$. Likewise, individuals hit the target in less time in the LASER task in the predictable condition, $F(1, 18) = 32.04, p < .01$. Accuracy was also compromised when the target moved randomly in the PURSUIT and LASER tasks ($F(1, 18) = 6.98, p < .01$ and $F(1, 18) = 49.8, p < .01$, respectively). The data from the monkeys did not differ significantly from the human data both in absolute and relative performance levels on any task.

Discussion. Clearly, these data do not corroborate the findings of Jaeger (1980) and others that rhesus monkeys fail to benefit from predictable target movement. The monkeys of the present investigation, like humans, exhibited better levels of video-task performance under conditions of predictable target movement relative to the random case. Consequently, one is led to conclude that rhesus monkeys—given the opportunity to learn that targets move predictably—may respond in ways that can be characterized as predictor-operator.

However, the caveat discussed earlier must be reconsidered: Comparable performance does not necessarily mean comparable processing—just as the species differences reported by Jaeger (1980) did not prove qualitative differences. This consideration, as well as the possibility of quantitative but not qualitative species differences in predictor-operator competency, were examined in the final experiment.

Experiment 3

In this experiment, rhesus monkeys and humans were tested on the LASER task under conditions comparable to those of Experiment 2. The LASER task was chosen because it seemed uniquely suited for the study of target prediction. In order to hit the target and end a trial efficiently, individuals must to some degree predict, as shots must be launched in such a way that the movement of the target is matched with the trajectory of the shot so as to cause an intersection in space and time.

The LASER has an additional feature that made it singularly interesting for this experiment. LASER shots were fired on the screen in an isomorphic direction to the angle of joystick deflection. Changes in the angle of joystick deflection in excess of 90° while any shot was on the screen, however, caused that shot to be aborted and a new shot to be fired at the new angle of deflection. These “aborted shots” were not reflected in the data analyzed in Experiment 2, but were maintained as separate, unexamined data for each trial. Thus, comparable performance in the number of unaborted shots required to hit the target, as in Experiment 2, could mask differences in response strategy that might be revealed in analyses of aborted shots.

Methods. The two rhesus monkeys from the previous experiments were tested as before. Each produced 1000 LASER trials with either a predictably moving or a stationary target. Ten human volunteers (ages

18–33; 6 women and 4 men) were also tested, each on 100 trials per movement condition.

Analyses. Appraising the degree to which an individual or species may respond as a predictor-operator requires some method of quantifying both the potential strategies for responding and also the topography of observed responses. Washburn and Rumbaugh (1992; Washburn, 1992) recently proposed a means of analyzing CHASE task response topography and argued that rhesus monkeys, like humans, tend to move to where a target is going rather than to where a target is. This same method was used to analyze the LASER shot paths.

One criticism of this method, however, is that comparison of practiced performance by rhesus with relatively unpracticed performance by humans may offer only the appearance of species similarities. The LASER task permits one way of identifying the effects of practice by dissociating the perceptual aspects (e.g., prediction, or determining where to shoot for most efficient intersection with the moving target) from the motor aspect (i.e., precision in joystick movement) of psychomotor responding. By testing individuals under conditions of no target movement (so that prediction is not required), a standard error of movement measure can be obtained. This measure can then be employed in the analysis of responses to predictably moving targets, producing a measure of the degree to which responses are predictive over-and-above individual or species differences in motor control.

For each trial in which the target remained stationary, the angle required to hit the target was computed and compared to the observed angles of each shot fired. The average deviation of observed shots about the optimal shot angles was computed for each individual as a measure of motor precision. Simple regression produced for each individual an equation for adjusting observed shot angles according to this motor measure (i.e., for predicting "where the individual was trying to shoot" based on "where the individual did shoot").

On trials in which the target moved, a similar procedure was employed to assay the degree to which individuals responded predictively, that is, to where the target was going. For each trial, the observed angle of each shot (O'), adjusted for the motor error measure using the individual-specific regression equation, was computed and compared to the computed angle of perfect prediction (P) and the angle of no prediction (T , or the angle subtended required to shoot directly at the target; see the results section for a depiction of these angles for a sample trial). The semipartial correlation coefficient of O' and P , removing that portion of P that correlates with T ($r_{O'(P,T)}$), provides a measure of the unique relation between observed responding (adjusted by motor error) and optimal prediction.

For each aborted shot, two measures were taken. First, the proportion of the distance from the turret to the target that the shot had traversed

TABLE 4
Percentage of Shots as a Function of Whether the Shot was Aborted
and Whether the Shot Hit/Would Have Hit the Target

Was the shot aborted?	<i>Did/would the shot hit the target?</i>			
	Rhesus		Humans	
	Yes	No	Yes	No
Yes	4.90%	37.64%	3.81%	37.26%
No	27.19%	30.27%	26.00%	32.93%

was computed. It might be determined that a particular shot had travelled half the way to the target before it was aborted). Second, for every aborted shot a determination was made as to whether the shot would have, in fact, hit the target had it been permitted to continue across the screen.

Results. As in Experiment 2, no significant difference was found between the number of unaborted shots required for humans and rhesus monkeys to hit moving targets in the LASER task ($p > .05$; $M(\text{Humans}) = 2.98$ shots; $M(\text{Monkeys}) = 2.52$ shots). A more interesting analysis is the examination of aborted shots. The patterns of aborted shots were similar for the two species. Table 4 reveals the average proportions of shots taken by the individuals as a function of whether the shots were aborted and whether the shot hit (or would have hit) the target.

Note that 88% of the shots that the monkeys aborted would have missed the target (and 91% for the humans). Additionally, the distance that each of these errant shots had travelled before it was aborted was compiled for each individual. The rhesus monkeys could identify and abort an errant shot after it had travelled, on average, 73% of the distance between the turret and the target. Similarly, humans aborted errant shots that had traversed an average of only 60% of the distance to the target; these differences did not approach statistical significance. Thus, individuals from both species were able accurately to identify and to abort errant shots *well before they reached the target*.

Finally, analysis of the path of responding (the actual angles of each shot) confirmed these findings. The rhesus monkeys were in fact slightly more accurate in shooting at stationary targets (mean shot error = 19.1° for the monkeys, 26.5° for the humans). However, these differences were not statistically significant, indicating that the motor performance of simple tasks such as LASER show relatively little improvement with practice. Using regression techniques, following the procedures outlined by Washburn and Rumbaugh (1992a,b), humans were found to predict better than did the monkeys, $F(1, 18) = 4.60$, $p < .05$. That is, responses

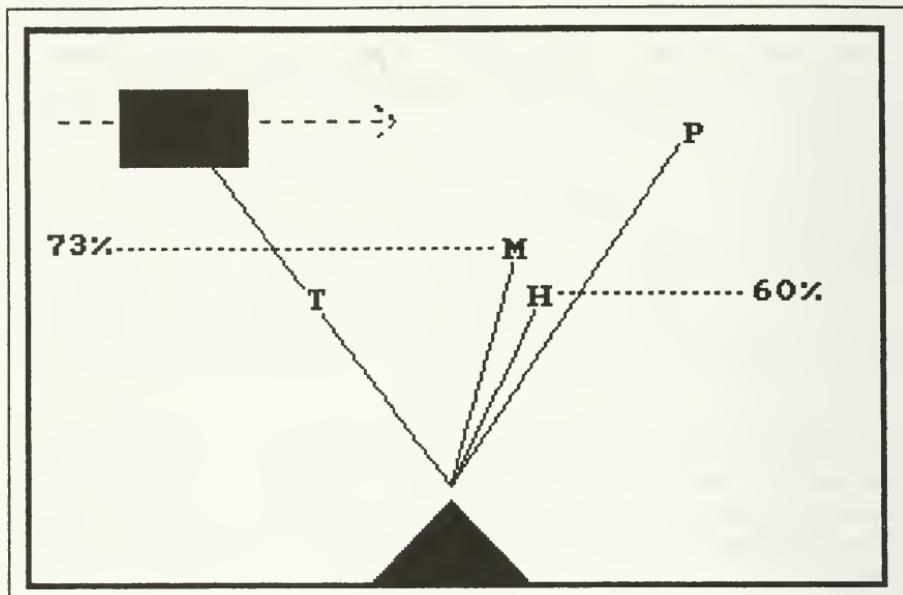


FIGURE 2. A sample trial depicting the angle at which a shot must be fired directly at the target (T), the angle for most efficient intersection with the moving target (P), a typical shot for humans (H), and a typical shot for rhesus monkeys (M), given these locations. (In an actual LASER trial, the shot would be a short line that moved slowly across the screen.) Note the direction of target movement, and the marks indicating for these angles the point at which errant shots would be, on average, aborted by the two species.

by human subjects more accurately approximated the "perfect shot angle" than did shots by the monkeys. However, responses for both species were found to correlate significantly and uniquely with the hypothetical predictive path ($r_{O(P,T)} = .67$ for the monkeys and $.84$ for humans). Figure 2 illustrates these findings for a sample trial.

Discussion. From these results it is clear that both rhesus monkeys and humans tend to respond as predictor-operators. Responses by both species tended to approximate the hypothetical "optimally predictive" shot angle. Additionally, individuals from both groups evinced the capacity to distinguish accurately and quickly which shots were likely to hit the target and which were errant and could be aborted. These findings appear not to be a function of simple motor differences between the species due to differential practice, but rather reflect similarities and differences in the facility with which each species responds predictively.

Understanding psychomotor performance requires analysis of motor competency and predictive competency—both which may exhibit quantitative differences between the species. Here, as in Washburn and Rumbaugh (in press), the appropriateness of rhesus monkeys as a model of human psychomotor performance is supported, as no qualitative difference of the type suggested by Jaeger (1980) and others was found.

GENERAL DISCUSSION

Similar comparative applications of data from nonhuman animals to questions of interest to human factors abound. Ongoing research at our laboratory illustrates a spectrum of comparative investigation. Chimpanzees' competency for language and counting is being studied to understand how these processes may benefit from keyboard technology. Rhesus monkeys are studied to determine how the processes of attention, memory, and learning may effect computer-task performance by humans as well as macaques. The benefits of comparative investigations such as these are numerous. Heuristic, practical, ethical, and theoretical considerations sanction the utility and even necessity of such investigations.

The degree to which studies with nonhuman animals will successfully generalize to an understanding of the human-machine interaction will ultimately depend on how carefully we identify those factors that influence the nonhuman animal-machine relation. Thus, it is concluded that understanding the interface between psychology and technology will depend on the coordinated use of both strategies of "doing human factors research with nonhumans."

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HUMAN FACTORS, PSYCHOLOGICAL FACTORS, AND AFFIRMATION OF CONTINUITY

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The papers in this issue have presented a wealth of information from a variety of studies about factors that influence behavior. A key question has been and remains, "To what degree can one generalize from studies of nonhuman animal behavior to humans?" In years past, it has been argued that the study of animal behavior can tell one something about basic conditioning and learning phenomena that might apply to humans, but the emphasis was on the word *basic*. The argument maintained that the really important behaviors and capacities that differentiated humans from all other animals (e.g., complex learning, thinking, logic, and particularly *language*) had no meaningful parallel or analogue in animals.

The archaic Cartesian framework of viewing animals as *beast machines* without feeling and cognition (Descartes, 1637) pervades the human view of animals even to this day. It denies animals the status needed to ensure their humane care, survival, and respect. Taken literally, it would totally constrain most research in comparative psychology. The Cartesian attitude towards animals is one that can serve to foster neglect of animals and, by implication, disregard for their welfare and survival as species.

The Cartesian framework is, of course, incompatible with the Darwinian principle of continuity, the essence of evolution (Darwin, 1871). Evolution could not produce *Homo sapiens* as a species apart from other animals. Evolution could produce, or select for, human characteristics only on the basis of what had been put in place as adaptive characteristics in other mammals (Darwin, 1872). Thus, the principle of continuity in evolution suggests the probability that closely related life forms will have similar anatomies, similar biologies, and even similar psychologies. That *Homo sapiens* and the chimpanzee, *Pan*, are very closely related in terms of DNA suggests that similarities might be detected in comparative stud-

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ies of their psychology (Andrews & Martin, 1987). But would they reveal similarities in processes of language?

Although the field of ape-language research has been very controversial, a recent controlled study (Savage-Rumbaugh, Murphy, Sevcik, Williams, & Rumbaugh, 1992) reveals that, given appropriate early rearing, the chimpanzee can come to comprehend human speech at least at the level of a 2½ year-old child and to employ grammar in its productive use of symbols so as to achieve communication at least at the level of a 1½ year-old child. The chimpanzees were reared essentially as though they were human infants and, consequently, had the opportunity to hear speech and to observe the consequences of the use of speech and visual symbols. Thus reared, the chimpanzees' comprehension of language far outpaced their productive use of symbols in a manner reminiscent of the human child's comprehension of speech far outpacing its ability to talk. It would appear that the rearing environment of the chimpanzees had enabled the brain to express a fuller potential for functional plasticity and in a direction that approximates that for the human child. Early exposure to language apparently set the cognitive stage for later acquisition of linguistic skills.

The point of these findings is that there is now strong evidence for continuity between chimpanzees and humans *even for language*. Consequently, it is no longer justifiable to argue that the study of animal behavior cannot assist in understanding human behavior because humans and only humans have language!

Developing new research methodologies that measure basic parameters of psychological functions in human and nonhuman animals should be a primary focus of future scientific endeavors. Science has been, and always will be, a function of available techniques and technology. Fortunately, several comparative psychologists have now learned how to use advanced computer technology in ways that allow for *direct and equitable* comparisons to be made between the competencies of animals and humans (Hopkins, 1991; Hopkins, Morris, & Savage-Rumbaugh, 1991; Rumbaugh, 1990; Rumbaugh, Richardson, Washburn, Savage-Rumbaugh, & Hopkins, 1989; Washburn, Hopkins, & Rumbaugh, 1989; Williams, Haddad, & Strobel, 1989). Perhaps most poignant is the development of software that permits one to teach monkeys, apes, and humans the rules of complex tasks entailing elaborate operations on the part of the individual.

Both authors of this paper independently demonstrated, with their colleagues, that nonhuman primates can learn to use joysticks to control complex events on a monitor (Williams, 1988; Rumbaugh et al., 1989). Individuals will even work just for the opportunity to manipulate their physical/perceptual world and to engage in a cognitively challenging task for reasons other than obtaining food and drink (personal observation). Animals are not motivated solely by their physiological need for food

and nourishment. As is true for humans, they have need to seek change, to obtain challenge, experience visual stimulation, and so on.

Forcing animals to attend to a task is no longer necessary and is, in fact, ill-advised. Tasks can be designed so as to become intrinsically motivating to nonhuman primates (Williams, 1990). Their behavior, in this context, reveals that we have profoundly underestimated their capabilities to date because of the limitations set forth by traditional methodologies and earlier technology.

New technology, coupled with highly creative frameworks advanced by authors of the papers in this issue, is bound to increase our knowledge in new and exciting ways. This is perhaps especially true regarding what we can learn about the complex cognitive abilities of humans in environments where, because of risks and costs of operations, it would seem prudent to first employ animals as models.

A new day is at hand—a day that has very strong and positive implications for the study of human factors. It is a day which allows for a great deal to be learned about human factors through the study of animal behavior, if one goes about such studies with the advantages of a comparative psychological perspective.

Validation of this view is certain. The questions that remain, and they are very difficult questions, address the specifics. In other words, in what situations and to what degree can we extrapolate from the behavior—the psychology of a primate—to the behavior of a human? Generally there will be limits imposed upon extrapolations from animal to human data and vice versa. Notwithstanding, within those limits, good science and good preparations can be made for subsequent enhancement of the human endeavor.

Human factors as a specialty, from our perspective, might well become a subsystem of *comparative psychological factors*. In the article by David Washburn, we find convincing support from several experiments for the belief that all organisms possess several common cognitive competencies that differ only in quantitative dimensions. These shared cognitive competencies have been clearly defined and efficiently studied in tasks requiring humans and nonhumans to interface with computers. For example, his data suggest that monkeys and humans both may function as predictor-operators if given the appropriate training. Because this conclusion directly conflicts with an earlier suggestion that only humans possess this capability, it follows that other areas of cognitive function should be reviewed and reconsidered with new research techniques availed by computer technology. Assuming that monkeys can now serve as valid models of human psychomotor performance, we can now seek to understand the quantitative complexities surrounding the interfacing of animal (both human and nonhuman) to machine. The more we understand the mechanisms and processes by which other organisms solve problems, organize their perceptual world, direct their attention, and recall and

utilize past experiences, the better we may understand ourselves and our unique abilities as well as our limitations associated with mental retardation, brain damage, aging, and so on.

This case is clearly presented in the article by Duncan White which describes the contributions of the cat to comparative psychology and thus to human factors. These contributions are impressive in the areas of learning, vision, audition, and medical science. But one can immediately see from the references that little research has been conducted recently, especially in the areas of learning and problem solving. There is no doubt that the cat has been an acceptable model for addressing many questions in medical science and psychology. We now need to focus the attention more on addressing specific questions in comparative psychology using the new computer technologies previously described. Changing the topography of the response to suit the cat's specific anatomy is no obstacle. Once this is achieved, we might well access cognitive competencies on a level never before realized. Models of foraging behavior, cost-benefit ratios, decision-making strategies, prediction, memory, and visual/spatial tracking are examples of areas that could be addressed with the new methodologies. This should result in a wealth of knowledge again applicable to both humans and animals.

Along with advanced technology comes the need for new theoretical approaches, experimental designs and procedures, and novel implementations. Roger Thomas has convincingly reminded us all of the bi-directionality of scientific applications between human and nonhuman animals. We should not be constrained by the idea that animals can serve only as models for human questions; humans can serve as models to test questions evolving from animal research. This bi-directionality can only serve to help validate results and to shed light on new perplexing cognitive issues, especially those of counting and oddity/sameness-difference concept hierarchies.

In due course, future studies, like those in this issue, will likely conclude what many have suspected for a long time, and that is that the essence of psychology is *general comparative psychology*, not just human behavior. Such studies will also serve to underscore the perspective that animal research should be carried out with a new sense of continuity that binds us more closely—far more closely—than Descartes could ever allow or envision. By accepting this approach, we will develop a greater appreciation for animals and will come to value and respect our relationship with them. Such a perspective should serve the survival interests of all!

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